Non-Reciprocal Beam Transmission in Slanted Fiber Bragg Grating with Axially Asymmetric Cladding

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1. Introduction

Fiber Bragg gratings (FBGs) [1] reflect back the specific wavelength light coincident with the Bragg phase-matching condition. By slanting the grating, the guided core mode may couple to radiation modes. Furthermore, replacing a part of intrinsic clad material to the lower refractive-index material (LRIM), different beam coupling to radiation modes between the forward and the backward propagation light beams may emerge.

We propose a novel slanted FBG structure with axially asymmetric cladding materials with different refractive indices [2]. Different beam coupling mechanisms in this structure and theoretical calculation results are described. Finally, we show this device may be applicable to an optical isolator.

2. Structures

Figure 1 shows the cross sectional view for the proposed optical fiber structure with slanted gratings in the fiber core. In this figure, the refractive index for the cladding in the upper part of the grating n_{mt} is lower than the intrinsic cladding material n_{cl}. Guided mode beams incident from the backward direction will be diffracted and couple to the radiation modes in the cladding with lower refractive index n_{mt}. On the other hand, guided mode beams from the forward direction will never couple to radiation modes.

Figure 2 shows the Bragg phase-matching condition among gratings, guided modes and radiation modes. The upper half circle n_{mt} represents the magnitude for the refractive index of the LRIM, and the lower one n_{cl} represents that for the intrinsic cladding. The parameter n_{gm} is the guided-mode refractive-index which is given as optical fiber parameters. Asymmetric cladding structures yield asymmetric circles. In this figure, the z-axis is selected as the beam propagation direction. The vector κ_g is phase-matched to β_{mt}, however we may also match the vector to β_{cl} by changing the grating pitch and slant angle. In this case, light beams from the backward direction are diffracted, and those from the forward direction transmit through the grating. The parameters κ_g, ψ and θ_g indicate the grating vector, the coupling angle to radiation modes and the slanted angle, respectively. The Bragg phase-matching conditions are given by

$$|\beta_{gm}| + |\beta_{mt}|\cos\varphi = |K_g|\cos\theta_g \quad \text{and} \quad |\beta_{mt}|\sin\varphi = |K_g|\sin\theta_g, \tag{1}$$

where β_{mt} and β_{mt} are the propagation constants for the guided mode and the radiation mode, respectively. These parameters are represented as follows

$$\beta_{gm} = \frac{2\pi}{\lambda_{Bragg}} n_{gm} \quad \text{and} \quad \beta_{mt} = \frac{2\pi}{\lambda_{Bragg}} n_{mt}, \tag{2}$$

where λ_{Bragg} is the Bragg wavelength. A grating vector is optimized to couple the backward guided-mode vector with radiation mode vectors of the LRIM. For the optimized grating, light beams from the backward direction couple to radiation modes in the material with lower refractive index, however those from the forward direction do not radiate and transmit through the grating, because the Bragg phase-matching conditions are not satisfied. Therefore the guided mode propagation may be non-reciprocal in the slanted grating.

3. Calculation Theory

In many cases, FBGs have been analyzed by the coupled mode equations [3][4] or the stratified medium approximation [5]. However, it is difficult to calculate models including radiation modes. Then, we have used the calculation theory for scattered power of radiation mode couplers derived from the distributed antenna theory [6]. In this theory, the grating is treated as a sum of partial reflectors.

Figure 3 shows the Cartesian coordination system for calculations. In the coordinate system, the z-axis is selected as the beam propagation direction. The gratings are formed along the z-axis with the slanted angle θ_g at the interval of Λ_g (grating pitch) in the length of L (grating length). The gratings are formed in the optical fiber core, however the distributed antenna theory assumes that the gratings are formed in the infinite cladding region. The parameter $E_{incident}(x,y,z)$ indicated the magnitude for the electric field of light beams propagated from the -z direction. The light beams are diffracted by the gratings and they form the magnitude for the electric field $E^{mt(cl)}_{scatter}(R,\phi,\psi)$ at the point (R,Φ,Ψ) where is far from the gratings. By using the Fraunhofer diffraction, the parameter $E^{mt(cl)}_{scatter}(R,\phi,\psi)$ is represented as the triple integral

$$E^{mt(cl)}_{scatter}(R,\phi,\psi)=\frac{k^2 e^{i\beta_{mt(cl)}R}}{4\pi R} \times \iiint e^{i\beta_{mt(cl)}\delta R}\,\delta n_{mt(cl)} E_{incident}(x,y,z)\,dx\,dy\,dz \qquad (3)$$

where k, $\delta n_{mt(cl)}$, δR are the wave number, the refractive index variation along the fiber axis in the core region, the distance between gratings and the electric field of the incident light beam, respectively. They are represented as follows.

$$\begin{aligned}\delta n_{mt(cl)} &= 2n_{mt(cl)}\Delta n\, W_{grating}(r)\cos\left\{\left(\frac{2\pi}{\Lambda_g}\right)(x\sin\theta_g - z\cos\theta_g)\right\} \\ &= n_{mt(cl)}\Delta n\, W_{grating}(r) \\ &\quad\times\left(\exp\left\{i\left(\frac{2\pi}{\Lambda_g}\right)(x\sin\theta_g - z\cos\theta_g)\right\}+\exp\left\{-i\left(\frac{2\pi}{\Lambda_g}\right)(x\sin\theta_g - z\cos\theta_g)\right\}\right)\end{aligned} \qquad (4)$$

$$\delta R \approx -x\cos\phi\sin\psi - y\sin\phi\sin\psi + z\cos\psi \qquad (5)$$

$$E_{incident}(x,y,z) \approx E_0(x,y)e^{(i\beta_{gm}-\xi)z} \qquad (6)$$

where Δn in Eq.(4) and ξ in Eq. (6) and $W_{grating}(r)$ are the induced index by exposing ultraviolet lights, the loss coefficient in the grating and the window function of the gratings, respectively.

$$W_{grating}(r)=1\ (|r|<a)\quad or\quad 0\ (|r|>a) \qquad (7)$$

where a is the core radius. We assumed the electric field propagation in the S-FBG with axially asymmetric cladding as that in the step-index type single-mode optical fiber [7]. The magnitude for the electric field at the point (R,Φ,Ψ) is $E^{mt(cl)}_{scatter}(R,\phi,\psi)$ and its power is given by the Poynting vector.

$$S^{mt(cl)}_{scatter}(R,\phi,\varphi)=\frac{1}{2}n_{mt(cl)}\sqrt{\frac{\varepsilon_0}{\mu_0}}\left|E^{mt(cl)}_{scatter}(R,\phi,\varphi)\right|^2 \qquad (8)$$

We decide the radiation fields for the S-FBG with axially asymmetric cladding. On the fiber core boundary, we calculate the critical angles for the LRIM and the intrinsic cladding, respectively. We represent the critical angles $\theta_{critical}$ by using cutoff angles θ_{cutoff} (=90º- $\theta_{critical}$). Figure 4 shows the radiation fields on the xz plane. The upper part represents the radiation fields for the LRIM and the lower one represents for the intrinsic cladding. In this figure, θ^{mt}_{cutoff} and θ^{cl}_{cutoff} are the cutoff angles for the LRIM and the intrinsic cladding, respectively. Three dimensional radiation fields are obtained by distributions in the xy plane

The radiation mode powers for the LRIM and the intrinsic cladding are given by the radiation from the guided mode powers. These powers are given by the surface integrals for the Poynting vector indicated in the Eq. (8).

Therefore, the radiation mode powers P_{rad} for the S-FBG with axially asymmetric cladding are represented by the sum of those radiation mode powers. They are given by

$$P_{rad} = \int_{F_{mt}} \int_{q^{mt}_{cutoff}}^{p-q^{mt}_{cutoff}} R^2 S^{mt}_{scatter}(R,f,j)\sin j \, dj \, df + \int_{F_{cl}} \int_{q^{cl}_{cutoff}}^{p-q^{cl}_{cutoff}} R^2 S^{cl}_{scatter}(R,f,j)\sin j \, dj \, df \qquad (9)$$

The first term in Eq. (9) represents the radiation mode power for the LRIM, and the second term represents that for the intrinsic cladding.

4. Calculation Results

Table I shows calculation parameters. We assume the LRIM is air, and its refractive index is set at 1.0

Figure 5 shows the comparison of radiation mode powers for the forward and the backward propagation light beams. The grating pitch was changed to satisfy the Bragg phase-matching condition at each slant angle. In the angle region of lower than 17º which corresponds to a half of the critical angle between the fiber core and the LRIM, light beams will not be radiated to outer field of the fiber core because of the total reflection. On the other hand, in the angle of more than 17º, light beams will be radiated to outer field because the total reflection is never occurred. The radiation mode power for the forward direction is suppressed 30dB of the backward direction. The condition for the total reflection between the core and the intrinsic cladding will not be satisfied in the angle of lower than 17º, however the radiation powers from the intrinsic cladding are extremely small and the powers are not appeared in this result. The light beams will be radiated from the LRIM at the angle of more than 17º. Then, the radiation mode powers for the forward direction grow up in this region.

Figure 6 shows the comparison of radiation mode powers for the forward and backward propagation light beams, when the slant angle is fixed at the value of 20º, given from the Bragg phase-matching condition at this slanted angle. Non-reciprocal beam transmission between the forward and the backward directions are realized. The curve is not sharp. This means that we will have the redundancy for the misalignment in the grating fabrication processes. This result shows the alignment error is permitted at the maximum of 0.4º.

Figure 7 shows the comparison of guided mode powers for the forward and backward direction light beams on the same condition as Fig. 6. The forward propagation light beams pass through the gratings while the backward propagation light beams are radiated from the LRIM. This characteristic may be equivalent to the in-line optical isolator. This calculation model having a single grating period shows critical dependency on wavelengths. Wide distribution of the grating pitch (e.g. chirp grating) may reduce the wavelength sharpness. And the in-line isolator may be polarization independent because that wave number difference between two orthogonal modes, arose from degenerate LP_{01} by lacking cladding symmetry, is very small and chirped grating may widely cover the phase mismatch condition.

5. Summary

We proposed a novel slanted fiber grating with axially asymmetric cladding structures with different refractive indices. Theoretical calculation results successfully showed its non-reciprocal beam propagation and high unidirectional transmissibility. This device may be applied to an optical isolator. The fiber in-line isolator without magnetic field is very compact and not expensive because of that fabrication processes for an FBG have already confirmed. It may also be possible on planar lightwave circuits, $LiNbO_3$ or semiconductor waveguides. We believe it has fruitful merits such as isolator monolithically integrated with laser diodes [8].

References

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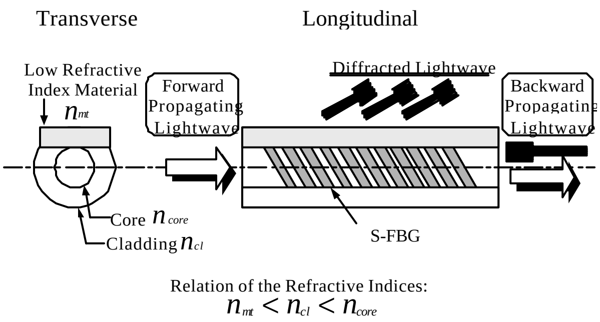

Fig. 1 Cross section for the S-FBG with axially symmetric cladding structures along the fiber axis.

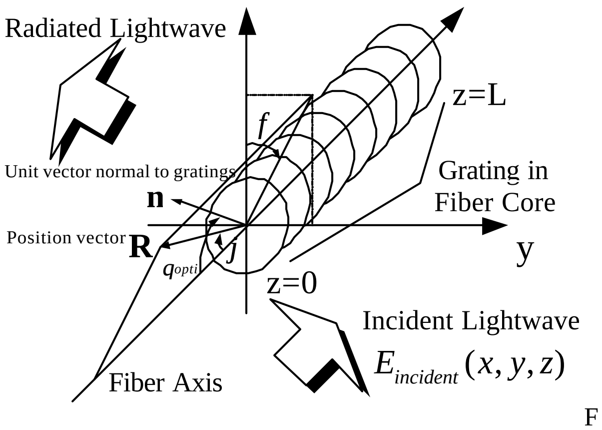

Fig. 3 Coordinate system for calculations

Table I Calculation parameters

Bragg Wavelength	1.55μm
Core Radius	5.0μm
Intrinsic Cladding Index Value	1.4525
Core Index Value	1.458
Lower Material Index Value	1.0
Grating Length	20mm
Induced Index	10^{-4}

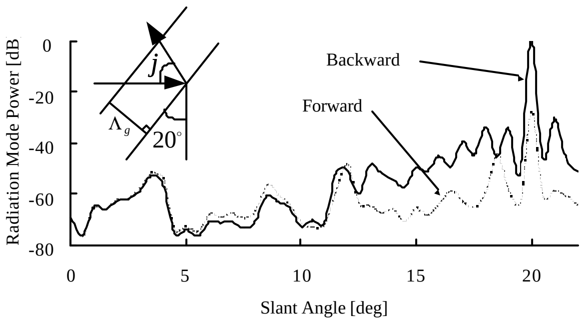

Fig. 6 Radiation mode powers (Grating pitch is fixed at 20° of optimized slant angle).

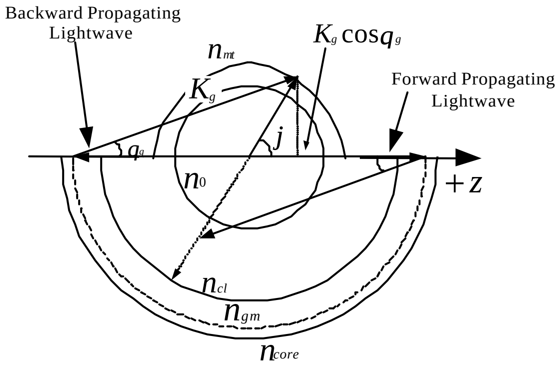

Fig. 2 Bragg phase-matching condition.

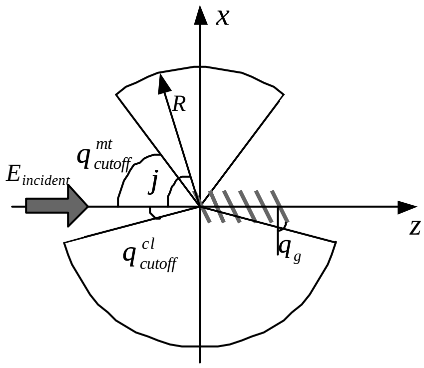

Fig. 4 Radiation mode regions

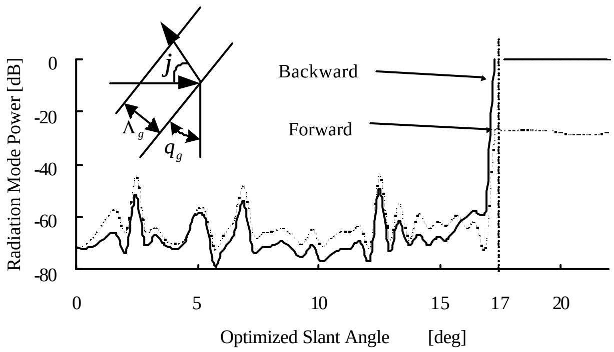

Fig. 5 Radiation mode powers
(Grating pitch is optimized at each slant angle).

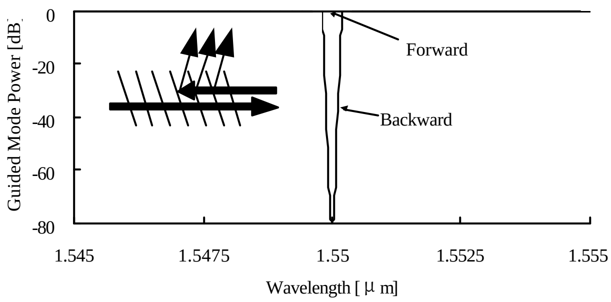

Fig. 7 Guided mode powers vs. wavelengths